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RESEARCH MEMORANDUM

COMBUSTION EFFICIENCIES IN HYDROCARBON-AIR
SYSTEMS AT REDUCED PRESSURES

By Robert R. Hibbard, Isadore L. Drell, Allen J. Metzler
and Adolph E. Spakowski

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUMCOMBUSTION EFFICIENCIES IN HYDROCARBON-
AIR SYSTEMS AT REDUCED PRESSURES

By Robert R. Hibbard, Isadore L. Drell

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SUMMARY

In preliminary results obtained with quiescent fuel-air mixtures and with small diffusion flames, combustion efficiencies close to 100 percent were obtained at pressures much lower than those found in turbojet combustors at altitudes of 60,000-feet; in general, efficiencies were high at pressures approaching the limiting values for inflammation. It is apparently possible to burn hydrocarbons with high efficiency at high altitudes if sufficient volume is available and undesired quenching processes do not occur. The reaction-zone volume required to effect a given rate of heat release rapidly increased with a decrease in pressure. It appears, however, that only a small fraction of the volume available in a turbojet combustor is required to effect the engine's design rate of heat release.

INTRODUCTION

The combustion efficiencies of current turbojet engines become substantially less than 100 percent at altitudes of 50,000 feet and higher. This reduction in efficiency appears to be primarily an effect of pressure inasmuch as, at full engine speed, the combustor inlet temperature and combustor average gas velocities do not vary appreciably over wide ranges of altitude above 30,000 feet. A decrease in pressure may affect combustion efficiency in several ways: (1) a possible increase in the time required to prepare a combustible fuel-air mixture from the liquid fuel spray, (2) a decrease in the ignitibility of the fuel-air mixture owing to the narrowing of inflammability limits and the raising of ignition temperature, (3) a decrease in the eddy diffusion spreading of the flame front, (4) an increase in the quenching effects, (5) a decrease in the rate of chemical reaction, and (6) possible other factors.

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This report presents the preliminary results of investigations on the combustion efficiencies obtained in the burning of hydrocarbons at subatmospheric pressures. Burning experiments were conducted on quiescent fuel-air mixtures and on simple diffusion flames in order to determine to what extent the chemistry of burning alone might be limiting the efficiency of turbojet engines at altitude. Although no systematic study has been made of the fundamental factors involved, the trends indicated by the preliminary data appear to be of sufficient interest to justify release at this time.

The investigation consisted of the three following phases:

- (1) The determination of combustion efficiencies in the burning of quiescent, premixed, fuel-air mixtures at low pressures and near the inflammability limits of the mixtures
- (2) The determination of combustion efficiencies of a small, wick-fed diffusion flame at reduced pressures
- (3) The determination of the reaction-zone volumes of a laminar propane-air diffusion flame as a function of pressure

From these experiments may be estimated the extent to which the chemistry of burning alone might limit the combustion efficiencies of turbojet engines at altitude.

PROCEDURE AND RESULTS

Efficiencies of Premixed Fuel-Air Mixtures

The combustion efficiencies obtained in the burning of premixed fuel-air mixtures have been estimated in a few cases from the analysis of the gaseous products pumped from an inflammability-limit apparatus. This apparatus consisted of a vertical glass tube (50-mm I.D. by 4.0 ft long) with a hot-wire ignition system at the lower end. A Toepler pump was used to pump the reaction products into a portable Orsat-type apparatus. The percentages of carbon dioxide, oxygen, carbon monoxide, unsaturated hydrocarbons, hydrogen, and saturated hydrocarbons in the mixtures were determined using potassium hydroxide, chromous chloride, acid cuprous chloride, concentrated sulfuric acid containing silver sulfate, cupric-oxide oxidation at 300° C, and catalytic oxidation at 500° C, respectively. At fuel-air ratios leaner than stoichiometric, combustion inefficiencies were calculated as the heat of combustion still available in the products divided by the heat of combustion of the reactants. At fuel-air ratios richer than stoichiometric where there is insufficient oxygen to completely burn the fuel, the inefficiencies were taken as the amount of oxygen left in the products divided

by the amount of oxygen in the reactants. All mixtures examined were at pressures very close (12-mm Hg or less) to the limiting pressure for that mixture. The resulting data are given in the following table:

Fuel	Percent of stoichiometric fuel-air ratio	Pressure, mm Hg abs.		Combustion efficiency (percent)
		Limit mixture	Test mixture	
Methane	153	300	305	95
Ethane	81	38	50	100
	125	40	50	95
	125	40	40	95
Propane	62	90	92	95
	169	106	108	95
	251	110	112	30
Isobutane	80	90	92	100
	177	102	108	95
	278	82	84	35
Butene-1	133	34	36	90
	158	38	40	90
	311	106	108	35

Combustion efficiencies were 90 percent or greater in all tests, except for those very rich mixtures that contained more than twice the stoichiometric amount of fuel. In the burning of mixtures richer than 200 percent of stoichiometric, the flames did not fill the tube from wall to wall and only the center core of the mixture was inflamed. The low combustion efficiencies for these mixtures may therefore be due to wall effects.

Efficiencies of Wick-Fed Diffusion Flame

The efficiencies of a diffusion flame burning at reduced pressure were determined by burning a small, wick-fed lamp in a calorimeter. The apparatus, which was made by modification of an A.S.T.M. D90-47T sulfur-lamp assembly (reference 1), is diagrammatically shown in figure 1. By using *n*-tetradecane as the fuel and about four times the stoichiometric amount of air, it was found that the lamp had a blow-out limit of about 110-millimeters mercury absolute. The lamp burned about 2 grams of fuel per hour at all pressures. The heats of combustion were determined for *n*-tetradecane in this assembly at pressures as low as 120-millimeters mercury absolute; although the

lamp could be made to burn for short periods at slightly lower pressures, no run long enough to yield significant data was made below 120-millimeters mercury absolute. The heat of combustion of n-tetradecane at various pressures and the heat of combustion as determined in an oxygen-bomb calorimeter (reference 2) are given in the following table:

Pressure (mm Hg abs.)	Gross heat of combustion (cal/gram)
753	11,700
745	10,900
254	11,300
178	11,300
139	10,900
120	11,000
Oxygen bomb	11,320

Combustion efficiency is plotted as a function of pressure in figure 2; the efficiency is shown to be substantially 100 percent down to pressures within 10-millimeters mercury of the blow-out limit. The efficiencies obtained with a typical turbojet combustor at simulated rated speed, zero ram, and various altitudes are shown in figure 2 for comparison. The diffusion flame has considerably better efficiency at pressures equivalent to the combustor pressure at high altitudes.

Reaction-Zone Volumes of Laminar Diffusion Flames

Low-pressure diffusion-flame data were obtained from propane flames burning on a 0.674-inch inside-diameter burner in the apparatus diagrammatically shown in figure 3. The altitude chamber was essentially a 9-inch outside-diameter steel shell 18 inches long, which was fitted with a suitable spark-ignition source and a 2- by 6-inch observation port. The chamber was evacuated by a rotary oil-sealed pump. Chamber pressures were read from a dial-type gage and were accurate to ± 0.5 millimeter mercury. Air and propane flow rates, metered to ± 5 percent accuracy, were controlled to maintain at all times an over-all fuel-air ratio approximately one-half as rich as stoichiometric.

All data were obtained at a constant fuel-flow rate. After ignition, the chamber pressure was systematically lowered step-wise and the flame was photographed at each pressure point on 4- by 5-inch color film to approximately full size. The transparencies thus obtained were projected and the reaction zone, appearing as an intense blue band forming the flame edge, was traced. Each projected

tracing was divided into approximately 10 horizontal sections and the volume of each section calculated, assuming the top section to be a hollow paraboloid and the other sections to be hollow cylinders. The total reaction-zone volume of the flame was taken as the sum of the volumes of the projected sections corrected for enlargement due to projection. At pressures of 80-millimeters mercury absolute or greater, a partial masking of the blue reaction zone by the yellow flame tip prevented an accurate determination of the reaction-zone volume; values for these volumes may be less accurate than those obtained at the lower pressures. At pressures above 125-millimeters mercury absolute, the reaction zone became too thin and the flame too pulsating to permit any estimate to be made of the reaction-zone volume.

The reaction-zone volumes determined for the laminar propane diffusion flame at a fuel flow rate of 3.9 cubic centimeters per second metered at 22° C and 760 millimeters mercury absolute are given in the following table:

Pressure (mm Hg abs.)	Reaction-zone volume (cu cm)
122.5	4.2
102.5	5.2
90.2	6.0
79.6	9.5
70.0	12.2
60.0	15.2
49.8	17.4
40.0	22.7
30.0	34.4
25.0	35.9
20.0	44.4

A six-fold increase in pressure resulted in an eleven-fold decrease in reaction-zone volume.

These data were recalculated to show the volume in cubic inches required to release 1000 Btu per hour, 100-percent efficiency was assumed. The data are plotted against pressure in figure 4. A curve was faired through these points and extended to intercept a point calculated from an estimate of 7.0×10^8 Btu per hour per cubic foot as the upper limit of the rate of energy release from a hydrocarbon flame at atmospheric pressure. This estimate was made by Mr. A. J. Nerad in a private communication and was based on a fundamental flame velocity of 60 centimeters per second and a flame-front thickness of 0.03 centimeter. For comparison, the volume available in a typical turbojet engine to effect the design rate of heat release

is also shown in figure 4 as a function of combustor inlet pressure and altitude. This rate of heat release was based on the design rate of fuel flow assuming 100-percent combustion efficiency of a fuel having a heating value of 18,600 Btu per pound. The diffusion flame requires much less volume than is available in the engine to effect a given rate of heat release at any pressure but as the pressure is reduced, the fraction of the combustor volume required for the burning reaction increases.

DISCUSSION

Results both from the inflammability-limit experiments and from diffusion-flame calorimetry show substantially 100-percent combustion efficiency at pressures much lower than those at which a typical turbojet combustor gives considerably reduced efficiency. Data on quiescent, premixed, fuel-air mixtures show high combustion efficiencies down to within 12-millimeters mercury of the limiting pressures for inflammation and show efficiencies greater than 90 percent at absolute pressures of 50-millimeters mercury and lower for near-stoichiometric mixtures. A small diffusion flame having a blow-out limit at 110-millimeters mercury absolute yielded an efficiency of 97 percent at 120-millimeters mercury absolute. It is probable that a larger diffusion flame would have a combustion efficiency of substantially 100 percent at much lower pressures and it is equally probable that a premixed Bunsen flame would be equally as efficient at reduced pressures. In general, combustion efficiencies are close to 100 percent in these laboratory burning processes even at pressures less than one-half those found in the combustor of a typical turbojet engine flying at 60,000 feet and rated speed.

There are also indications that the reaction volume required to release the energy from flames is a small fraction of the volume available in a turbojet combustor. If the volume required to bring reactants to and remove products from the reaction zone is neglected, less than 1 percent of the combustor volume may be required for the actual burning reaction in turbojet operation at 40,000 feet. This would leave 99 percent of the combustor volume in which the processes of fuel atomization, vaporization, mixing, ignition, and hot-gas dilution could take place. At 60,000 feet, less than 5 percent of the combustor volume may be used for the burning reaction; at much lower pressures (of the order of 50 mm Hg abs.) 20 to 25 percent of the combustor volume may be required for the burning reaction, assuming the linear extrapolation of the design rate of heat release to be valid.

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In general, the results of these preliminary investigations indicate that the chemistry of burning is not directly limiting the altitude efficiencies of turbojet engines. If a flame is given the right environment, it will burn at close to 100-percent efficiency at pressures much lower and altitudes much higher than those now being considered.

SUMMARY OF RESULTS

Based on preliminary results from laboratory scale experimentation, it has been found that:

1. Much higher combustion efficiencies can be obtained at reduced pressures in the burning of quiescent fuel-air mixtures and in diffusion flames than are being realized in present turbojet engines.
2. Flames will burn with efficiencies of substantially 100 percent at altitudes well above 60,000 feet if sufficient volume is available and undesired quenching processes are absent.
3. Combustion efficiencies of near 100 percent are obtained in the burning of quiescent fuel-air mixtures at pressures quite close to the limiting pressures for inflammation.
4. The reaction-zone volume required to effect a given rate of heat release increases greatly with a decrease in pressure.
5. The volume available in a turbojet combustor appears to be many times that required by the burning process alone.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

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1. Anon.: Tentative Method of Test for Sulfur in Petroleum Products by the Lamp-Gravimetric Method. A.S.T.M. Designation: D90-47T. A.S.T.M. Standards on Petroleum Products and Lubricants, Nov. 1948, pp. 38-44.
2. Anon.: Standard Method of Test for Thermal Value of Fuel Oil. (Adopted 1919; rev. 1939.) A.S.T.M. Designation: D240-39. A.S.T.M. Standards on Petroleum Products and Lubricants, Nov. 1948, pp. 160-163.

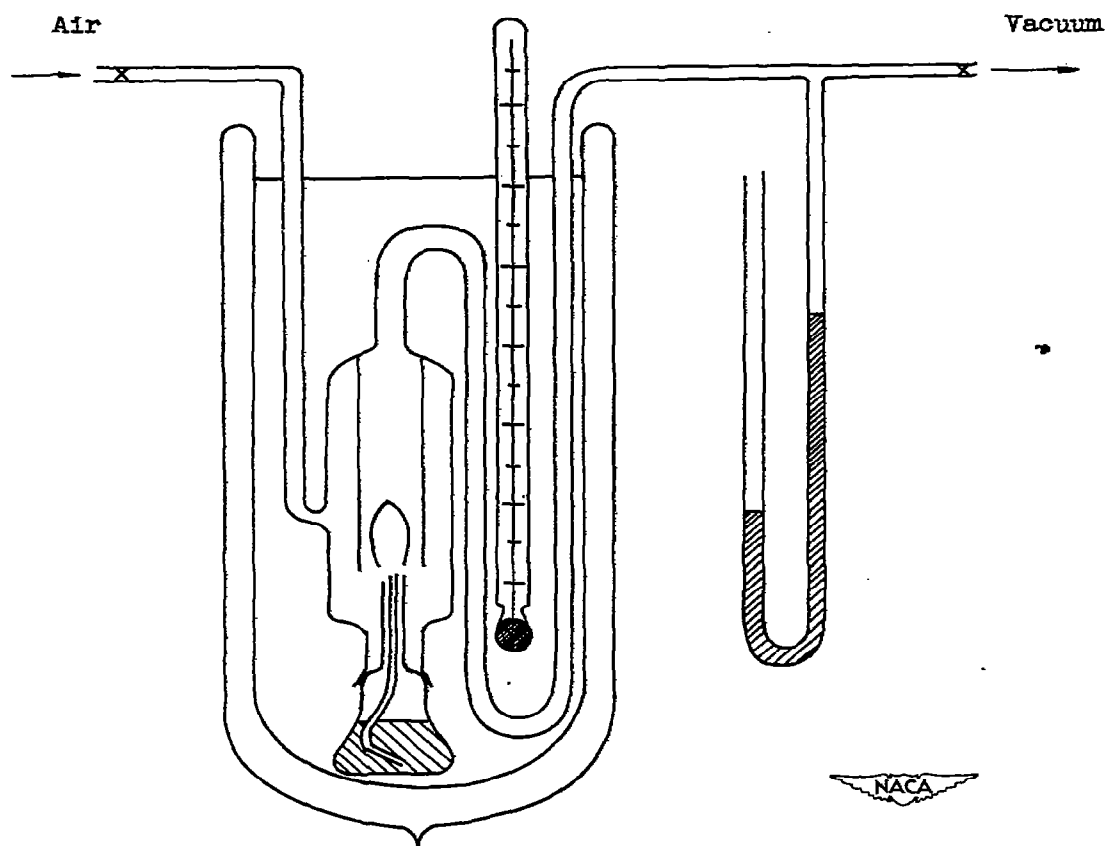


Figure 1. - Calorimeter.

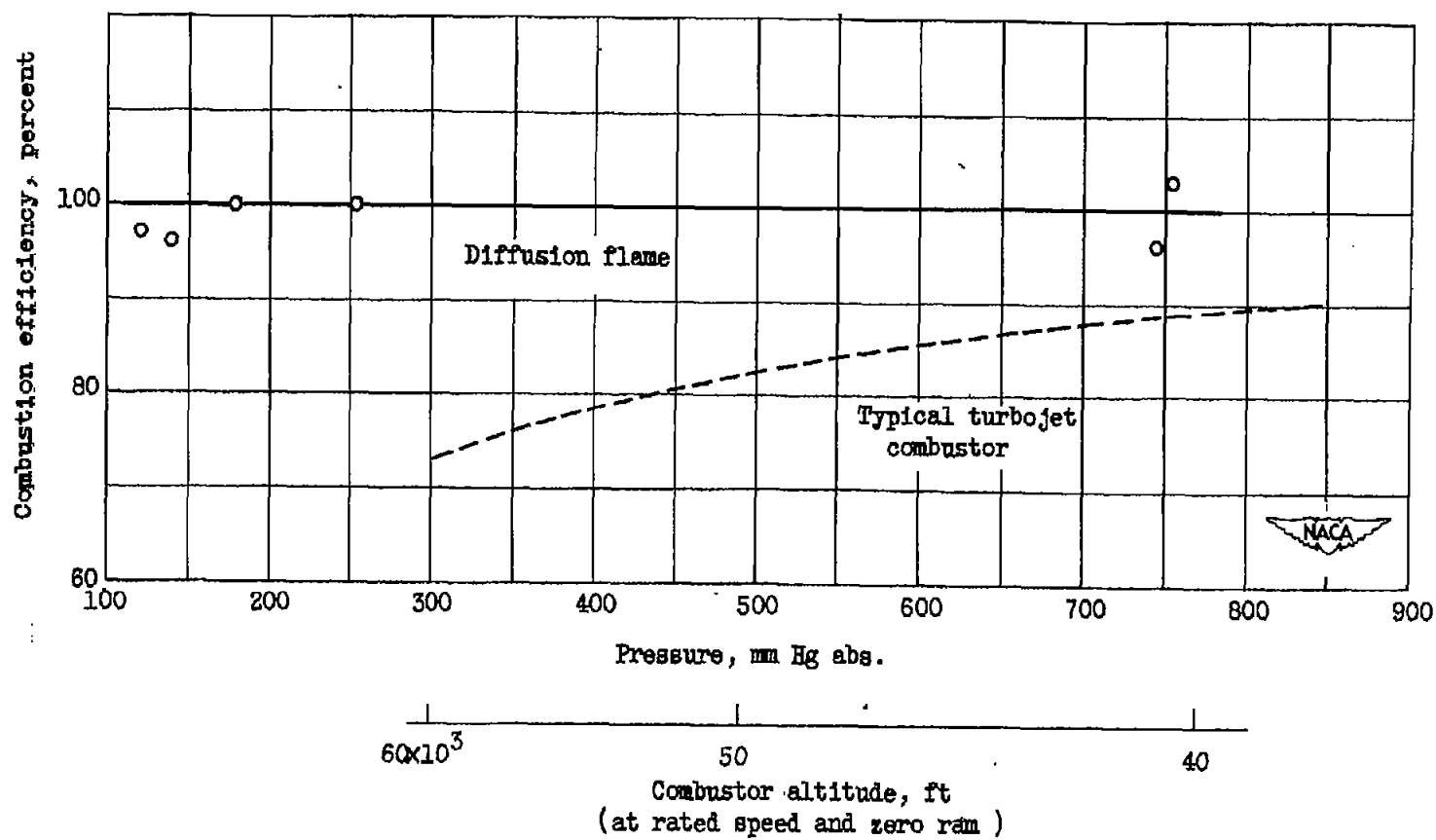


Figure 2. - Effect of pressure on combustion efficiency.

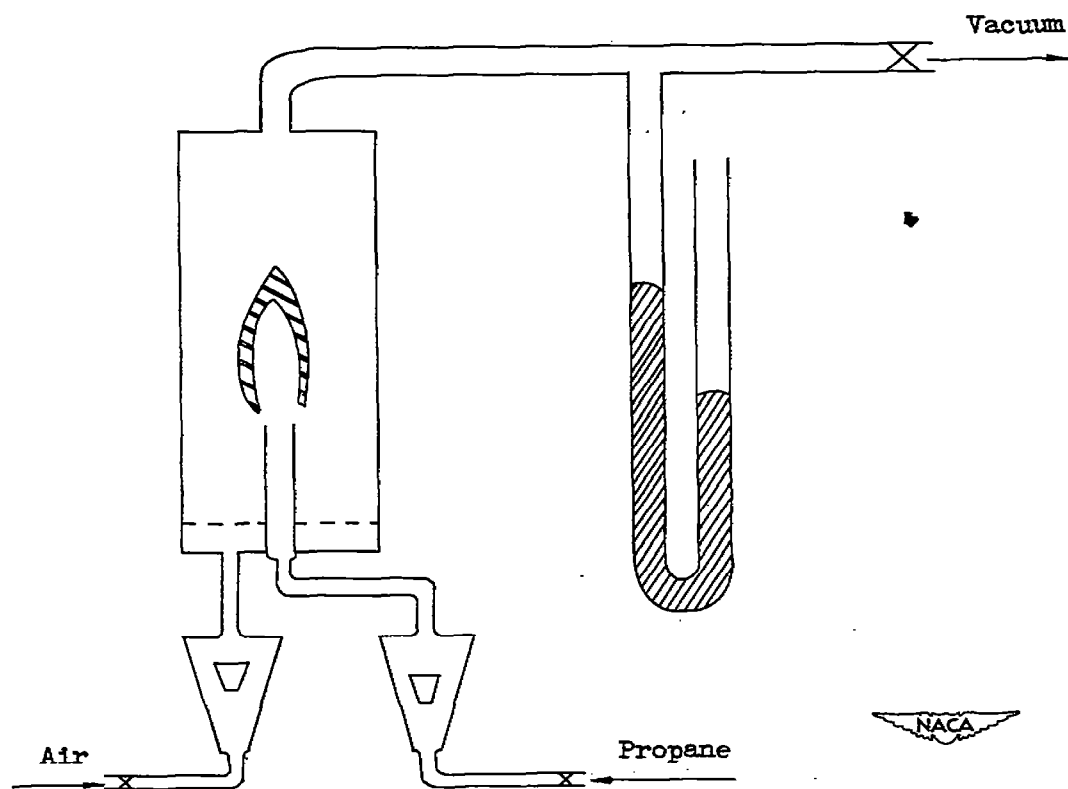


Figure 3. - Diffusion flame apparatus.

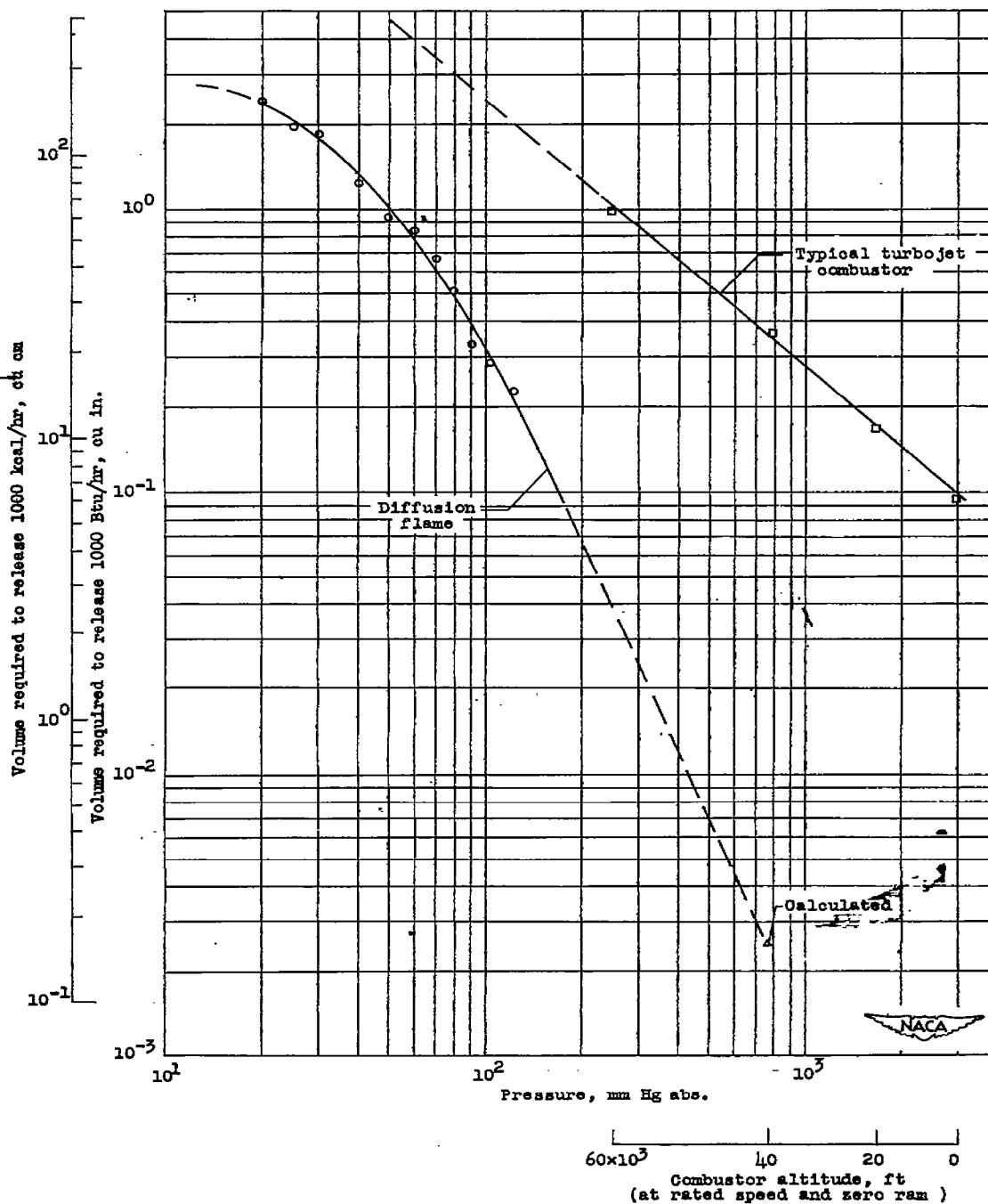


Figure 4. - Heat-release rates.